THE TIME MACHINE

Dating features on the Moon and Mars is guesswork. Scott Anderson is building a tool to change that.

BY ERIC HAND

The bits of rock on Scott Anderson's shelf are not much to look at, but they have stories to tell. In a plastic case is a greenish-grey rock, a 4.5-billion-year-old piece of the asteroid Vesta. Next to it rests a dark sliver of 2.8-billion-year-old lava from the Moon. Anderson, a planetary scientist at the Southwest Research Institute in Boulder, Colorado, picks up his favourite, a 1-gram slice of rock that cost him US$800. The flake came from Zagami, an 18-kilogram meteorite named after the Nigerian village where it was found in 1962. It is one of the rarest and most sought-after types of meteorite — a piece of Mars that was blasted into space by an asteroid impact and eventually landed on Earth. "Knowing what it is makes me excited to see it every time," Anderson says.

What Anderson wants from these far-flung fragments of the Solar System is elementary: their ages. Coaxing out that information is far more difficult. Zigzagging across his laboratory is a web of laser beams that feed into a mass spectrometer — all part of a geochronometer that Anderson is building. Like other rock-dating systems, this one computes an age from the radioactive decay of certain isotopes in a sample. What sets Anderson's system apart is his goal to shrink the whole operation down to something that would fit on a desktop. Then, rather than waiting for planetary fragments to fall to Earth, he wants to send his device to the planets.

Over the past few decades, planetary scientists have mapped the Solar System in ever more staggering detail. Cameras orbiting the Moon and Mars can zoom in on objects as small as dinner plates, and radars can penetrate several metres below the surface. But when it comes to the fourth dimension — time — they are as blind as ever. Scientists have hard dates for only nine places in the Solar System, all on the Moon: six Apollo sites and three Soviet Luna sites, from which samples were returned robotically. When did water flow on Mars? When did the Moon's volcanoes last erupt? Without dates, planetary scientists can only make educated guesses about some of their most pressing questions.

A portable, *in situ* chronometer such as Anderson's could revolutionize how researchers study the Moon, Mars or other rocky bodies. The costs of big planetary missions are skyrocketing; the $2.5-billion Mars Science Laboratory that is scheduled to land on 6 August is one of the most expensive Mars missions ever. But Anderson's tool could reduce future costs, in particular by avoiding the need for budget-busting missions to retrieve samples from other planets and haul them back to Earth. And the device could even find a wide audience on Earth, among geologists who could use it to map the ages of rocks in the field, rather than delivering samples to a lab and waiting months for the results.

Scott Anderson plans to finish the prototype for his portable geochronometer later this year.

MATTER OF SCALE

But first, Anderson has to transform the finicky set-up that sprawls across his lab into one that could fly in space. Other groups are trying to develop portable geochronometers, but Anderson's design has some advantages, and he is closer to completing a working prototype. At present, the half-built apparatus sits in the corner of his office: 160 kilograms of gleaming steel and aluminium, roughly the size of a two-drawer filing cabinet. He hopes to finish it later this year, and then he will bolt it into the back of a van and take it on a road trip. "We've been talking about how we could drive this to NASA headquarters and test this in the parking lot," says Anderson. At 44 years old, he is tall and boyishly earnest, but savvy enough to understand good public relations. He wants to persuade NASA officials to pay to build an ultra-lightweight geochronometer and then send it on a rover to the Moon or Mars.

Anderson will have to show not only that his chronometer is fast and light, but also that his dates make sense. Radiometric dates are some of the trickiest, most delicate and most disputed measurements on Earth. Anderson wants to transform what has been a laborious process of chemical extraction and analysis into a laser-based system, automate it and shrink it into a robot small and reliable enough to send

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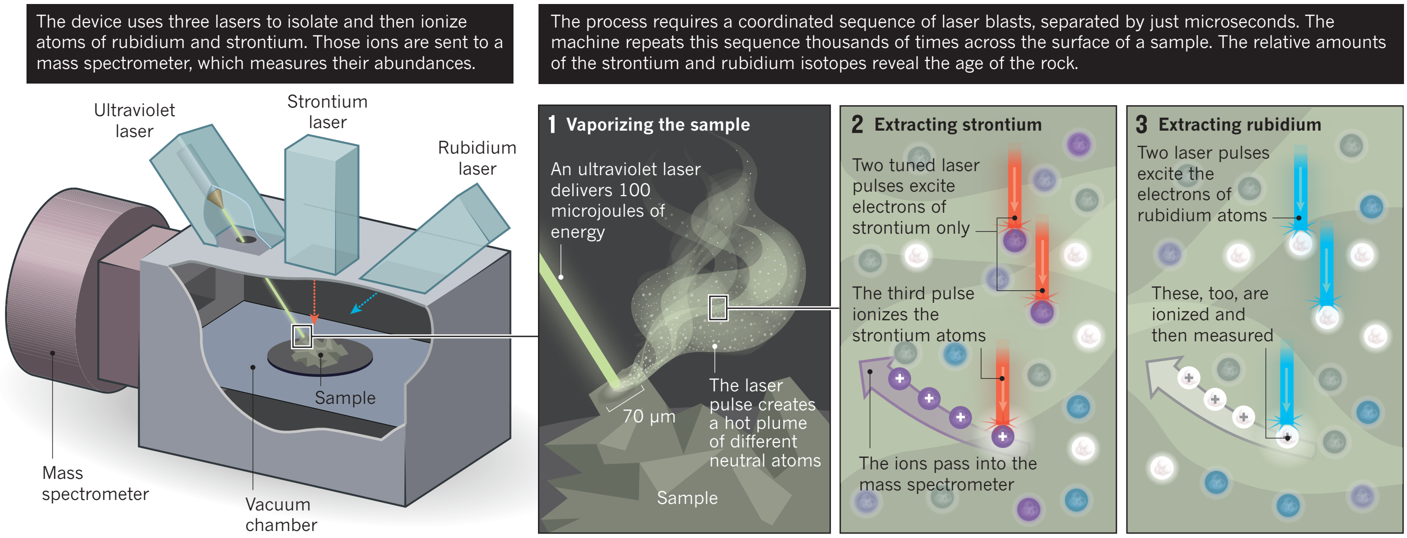
SPEED DATING

Researchers at the Southwest Research Institute in Boulder, Colorado, are building a device that can quickly determine the age of rocks by measuring the decay of radioactive rubidium-87 to strontium-87. The tool is designed to be small and lightweight enough to fit on a mission to another planet.



to another planet. "We're extremely sceptical of these things working," says Lars Borg, a chemist at the Lawrence Livermore National Laboratory in Livermore, California, whose three-person lab usually produces just two dates a year. "We really struggle to get these ages ourselves."

But this spring, Anderson used the full-sized version of his system to date a 1.7-billion-year-old piece of Boulder Creek granite that he chipped out of the foothills near his lab. Anderson's system computed an age of 2.05 billion years ± 130 million years — not great in terms of accuracy, but at least a proof of principle[1]. Next up will be Zagami — a precious rock sample that he does not want to put in the machine until it is ready.

Some researchers are now paying attention. "I would not have thought that they could progress this quickly," says Hap McSween, a planetary scientist at the University of Tennessee in Knoxville. "They're convincing me that there really is something to this."

QUESTION OF TIME

Anderson has wondered about the ages of rocks since he was a boy, when he would often tag along on field trips with his father, a sedimentologist at Temple University in Philadelphia, Pennsylvania. He learned about the principle of superposition — that younger layers are deposited on top of older ones — and how fossils can connect layers on different continents to a single epoch in the distant past. But the work was slow. "We spent hours staring at the same two feet of stone, getting sunburned and the bugs eating at you," he says.

As an undergraduate at Brown University in Providence, Rhode Island, Anderson discovered that he could avoid the insects by doing geology on other planets — where dates were even harder to come by. Planetary scientists had no fossils to work with, but on the Moon and Mars they had something else: thousands of craters left by large asteroids. In 1965, William Hartmann, a researcher at the Planetary Science Institute in Tucson, Arizona, developed a simple chronometer relying on the idea that surfaces marred by many craters should be older than ones with fewer blemishes. To date a surface, Hartmann used estimates of the rate of impacts over time, which he based on data collected on Earth[2].

This approach improved after the first Apollo rocks had been dated and the crater-count method was calibrated[3]. But even now, it yields dates with significant uncertainties — between 10% and 40%, Hartmann says. That is mostly because no lunar rock samples have been retrieved from surfaces between 1 billion and 3 billion years old. Scientists are eager to fill in that gap.

If chronology on the Moon is still uncertain, then Mars is a mess. The crater-count method does not work as well there, mainly because the wind, water and frost that sculpt the surface also erase craters. Translating the Moon's crater chronometer to Mars is a delicate business, says Barbara Cohen, a planetary scientist at Marshall Space Flight Center in Huntsville, Alabama, who is developing a rival portable chronometer. "On Mars, and on every other planet, all we're doing is extrapolating, for better or for worse, with a fudge factor." That 'fudge factor' could be erased with a few choice dates.

But those dates could do much more than simply calibrate the crater chronometer. With a portable system, researchers could decipher how long volcanism lasted on Mars and when it stopped. They could find out when the planet's warm, wet and possibly habitable environment gave way to the cold desert it has been for several billion years. "If any evidence is found for life, we sure as heck will want to know when it was there," says McSween.

These questions are some of the reasons that a generation of scientists have sought a mission to retrieve rock samples from Mars. In 2011, a sample-return mission was ranked the top mission priority for planetary science in the US National Research Council's decadal survey. But NASA's budget-minders baulked at the price tag for the project, which would have required three separate missions and a sample-handling facility — costing more than $10 billion in total over a decade. Anderson's device would cut out the return trip and do the dating on site. A Mars rover of any size is not cheap, but a medium-sized rover might be possible for about $1 billion. At that price, multiple dating missions could be sent to multiple locations. Doing the science *in situ* also sidesteps the costs of building a quarantined facility on Earth to handle the samples.

Defenders of the sample-return approach argue that there are many reasons for such a mission, beyond the mere dating of rocks. Searching for life in the samples would be the top priority, and that would be easier to do in a lab on Earth. But if Anderson and his competitors can demonstrate the viability of their portable geochronometers, support for a more complex and costly sample-return mission could diminish quickly. "I'd rather have five of those ages from five places on Mars than one sample return," says Hartmann.

Even before reaching the red planet, Anderson's device could win fans here on Earth. Geologists typically spend weeks or months out in the field and then haul sacks of rocks back from remote places for extensive analysis. Sometimes much of the effort is for naught — the samples may be unsuitable for dating, or the researchers may have picked up rocks that were older or younger than the period they wanted to study. A portable geochronometer that could produce a date within hours could solve those problems.

At the moment, some technical issues stand in the way. Anderson has spent the summer waiting for the delivery of a $200,000 laser that he needs to complete the device. In the meantime, he's had to jury-rig his lab so that several of his older lasers, cooled by a roomful of refrigerators and water pumps, shine into a vacuum chamber affixed to the brand-new, $700,000 mass spectrometer that will form the bulk of the portable prototype. One of the lasers, nicknamed Jill, is newly rehabilitated after a problem that announced itself with an acrid, burning smell. "Our best guess is something crawled in and committed suicide," says Keith Nowicki, a laser physicist in the lab.

In principle, Anderson's radiometric dating technique is similar to any other. It is based on the radioactive decay of one isotope into daughter isotopes according to a precise clock, a half-life, governed by nuclear physics. Anderson's method relies on rubidium-87, which decays to strontium-87 with a half-life of 48.8 billion years. This method, like any radiometric technique, typically requires monumental efforts. Researchers must first crush the rock and separate its minerals, often by hand. The minerals must then be dissolved in a strong acid, which goes through cation-exchange columns to extract the radioisotopes. These are dried and their abundance measured in a mass spectrometer. The steps can take months to complete. "The process is a pain in the neck," says Anderson.

LASER POWER

Anderson's method avoids some of these hassles by using tunable lasers to liberate and sort the isotopes all at once. During a visit, Nowicki and Anderson demonstrate the system on a piece of Boulder Creek granite. Even reflected light from the ultraviolet lasers is strong enough to blind, so the researchers first put on thick, $600 protective goggles that dim the room and colour it a sickly ochre.

Nowicki turns the lasers onto a wafer-thin slice of rock. Instantly, values for the abundances of rubidium and strontium appear as curves on a computer screen. Anderson is constantly tweaking the protocol for determining a date, but it always involves three basic steps (see 'Speed dating'). First, a blast of laser light vaporizes a smidgeon of the rock sample, creating a cloud of neutral atoms and a pit 70 micrometres around. Next, another, precisely tuned laser fires two shots, nanoseconds apart, to excite only the electrons in the strontium atoms in the cloud. A third shot rips those electrons away, turning the atoms into ions that are then whisked into the mass spectrometer. A microsecond later, three finely tuned shots ionize the rubidium atoms (which are still lingering in the cloud), and these are sucked into the mass spectrometer and measured. The process is repeated 20 times a second — and 3,000 times in the same place — and then the laser is pointed at a new spot on the sample's face. To date an entire sample, Anderson usually measures several hundred spots, which takes about a day and a half.

Other researchers, such as Cohen and John Eiler, a geochemist at the California Institute of Technology in Pasadena, are trying to develop *in situ* geochronometers that use potassium–argon dating, in which potassium-40 decays to argon-40 with a half-life of 1.3 billion years. Argon, a noble gas, tends to remain trapped in the crystal matrix of minerals. Potassium and argon are more abundant in common minerals than rubidium and strontium, which makes them easier to measure. But the potassium–argon system does not work as well for rocks that have been disturbed by high pressures and temperatures, which can cause argon to leak out and make the rocks seem younger than they are. And samples from Mars could have the opposite problem: argon-40 in the planet's atmosphere and mantle might have seeped into rocks, artificially inflating their ages.

Because each system has unique advantages and disadvantages, it may be best to put a couple of portable geochronometers on a rover, so that the results can be checked against each other. So Anderson has been busy forging alliances with Cohen and other former competitors to develop a viable mission proposal for a chronometer-laden rover.

They just might have a shot. In February, under intense budget pressure, NASA threw out its $10-billion, long-term Mars plan that would have begun a sample-return mission at the end of the decade. The new plan leaves only about $800 million for a Mars mission in 2018 or 2020, just enough for an orbiter, lander or, perhaps, an inexpensive rover.

MAJOR-LEAGUE PITCH

One day in June, Anderson flies to Houston, Texas, where NASA officials are holding a conference to solicit ideas for the new mission. Dozens of concept studies are vying for the attention of officials: robots that climb rocks, rovers that hop and autonomous skiffs that would explore Mars as they are whisked along by the wind.

Anderson gets ten minutes to present his team's concept. His chronometer would be mounted on an enhanced version of the Mars Exploration Rovers — Spirit and Opportunity — that landed in 2004. The new rover would have a life-detection experiment on board and might have room for a small sample cache, to preserve the chance of a future sample-return mission. Cohen's potassium–argon system would also squeeze aboard. By the time Anderson gets round to explaining his part — the rubidium–strontium geochronometer — he has three minutes to talk about the thing he has been working on for eight years.

> "IF ANY EVIDENCE IS FOUND FOR LIFE, WE SURE AS HECK WILL WANT TO KNOW WHEN IT WAS THERE."

He tells the audience that his rover would do important science and lay the groundwork for a sample return, without an absurdly high price tag. "More science, less commitment," he says.

Later, Anderson says that he has no idea how his concept was received by the NASA officials. "They're holding their cards pretty close to the vest." He knows that winning the flight opportunity is a long shot, so he is thinking about fallbacks. In 2015, NASA expects to solicit proposals for low-cost planetary missions, and Anderson plans to pitch sending a geochronometer to the Moon. But the bigger target is never far from his thoughts.

Anderson recently bought a 28-centimetre telescope — pretty big for an amateur — and installed it in his backyard in Boulder, which sits at 2,200 metres and has a clean view of the sky through the thin Rocky Mountain air. He has spent many an evening staring at the red planet — and imagining his timepiece at work on its surface. "I want to get it to Mars," he says. "I want to see it there." ■

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1. Anderson, F. S. *et al.* Presentation at the NASA Concepts and Approaches for Mars Exploration meeting, Houston, Texas; 2012. Available at http://go.nature.com/ahgamj.
2. Hartmann, W. K. *Icarus* **4,** 157–165 (1965).
3. Hartmann, W. K. *Icarus* **13,** 209–301 (1970).